On-Board Satellite Implementation of Wavelet-Based Predictive Coding of Hyperspectral Images

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***Abstract*— We present an algorithm for lossy compression of hyperspectral images generated by the MODIS instrument. To greatly reduce the bit rate required to code images, we use linear prediction between the bands. Once the prediction is formed, it is subtracted from the incoming band, and the residual (difference image) is compressed using the Set Partitioning in Hierarchical Trees (SPIHT) algorithm. The proposed bit plane-synchronized closed loop prediction simultaneously achieves high compression ratio, high fidelity, and simple on-board implementation.**

I. Introduction

Moderate Resolution Imaging Spectroradiometer (MODIS) data are collected from the Terra satellite at a rate of 11 megabits/second. These data are transmitted to earth, stored, and analyzed by various algorithms. Lossy compression techniques provide high compression ratios that allow reduction in bandwidth and storage requirements. The compression of hyperspectral images was investigated in [1] and [2]. In [3], the information content of hyperspectral data was studied and a lossless compression technique was proposed. The effect of data compression on cloud cover classification of MODIS data was examined in [4]. In this research, we use the Set Partitioning in Hierarchical Trees (SPIHT) algorithm [5], which is a wavelet-based state-of-the-art technique that codes images with both high compression ratios and high fidelity. SPIHT can be parallelized for implementation on FPGAs and therefore has a great potential for applications where the compression is performed on the satellite.

To reduce the bit rate required to code hyperspectral images, we use linear prediction between the bands. Each band, except the first, is predicted by a previous band. Once the prediction is formed, it is subtracted from the incoming band, and the residual (difference image) is compressed using SPIHT. The energy in the difference band is low and therefore, the difference band can be compressed with only a small number of bits.

All of the difference images are compressed to the same fidelity. To compute the exact difference between the incoming band and its prediction from a previous band, the encoder must have access to the decoded version of the previous band. Such a *closed loop system* however requires implementation of the decoder on the satellite, which greatly increases the complexity of on-board applications. In the proposed *bit plane-synchronized closed loop system*, both the encoder and the decoder simply use the same number of bit planes of the wavelet-coded difference image of the previous band for prediction. This enables the encoder to be less complex because while it must still do an inverse wavelet transform, full decompression on-board the satellite is not needed.

In this article we show the comparison between the open, half-open, closed, and the bit plane-synchronized closed loop systems. The proposed prediction method has very promising performance in that for the same fidelity, the average bit rate is only slightly higher than for the closed loop system, yet it permits a simple encoder for implementation on the satellite.

II. Set Partitioning in Hierarchical Trees

SPIHT is a progressive image coder, which first approximates an image with a few bits of data, and then improves the quality of approximation as more information is encoded. SPIHT creates an embedded bit stream in which the later bits refine the earlier bits. As shown in Figure 1, the encoder first performs a wavelet transform on the image pixels. Then, the wavelet coefficients are encoded one bit plane at a time. To achieve compression, the bit stream can be truncated at any time (see Figure 2). Note that bit plane encoding and decoding takes significantly more time than the wavelet transform.

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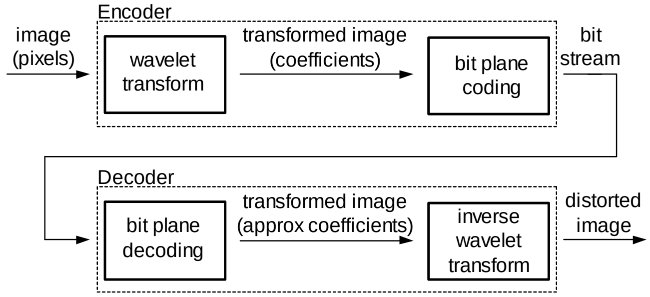


Figure 1. Block diagram of SPIHT.

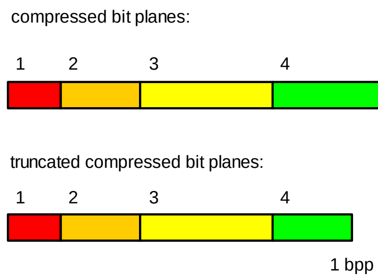


Figure 2. Bit plane coding.

III. SPIHT ON HYPERSPECTRAL DATA

We use prediction to take advantage of correlation between bands. As shown in Equation (1), first, the current band is predicted from a previous band B_j. Then, the difference D_i between the original band B_i and the predicted band P_i is computed. To recover the original band B_i, its prediction P_i has to be summed with the difference band D_i.

$$
\begin{aligned}
P_i &= a_{ij} B_j + b_{ij} \\
D_i &= B_i - P_i \\
B_i &= P_i + D_i
\end{aligned}
\tag{1}
$$

The prediction order of the bands has been optimized to minimize the overall distortion $\sum_i \left\| D_i \right\|^2$. The coefficients a_{ij} and b_{ij} are computed to minimize the norm of D_i using least squares optimization. All difference bands are coded to a target Mean-Squared Error (MSE).

Using prediction significantly improves the compression ratio. For example, as shown in Figure 3, for the Cuprite image (614x512, 224 bands, 16-bit integer data), when all of the bands are coded to an MSE of 100, using prediction decreases the required bit rate 5 times (from 8:1 to 43:1 compression ratio).

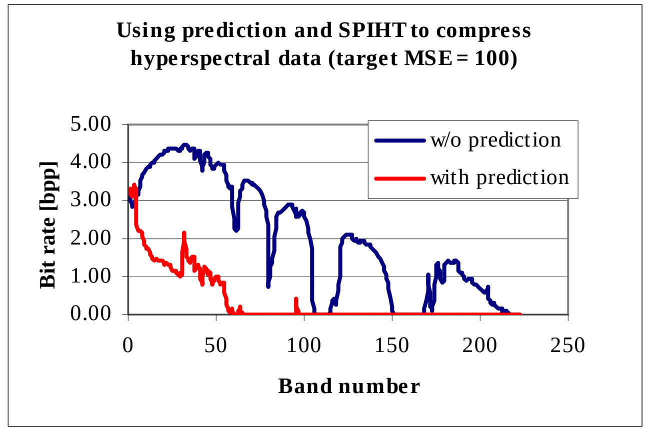


Figure 3. Comparison of bit rates required to code the hyperspectral data to MSE=100 with and without prediction.

IV. PREDICTION IN SPIHT

To predict the currently coded band, a previous band is needed. The previous band used for prediction can be the original or the decompressed band. In this research, we investigated four types of prediction: open loop, half-open loop, closed loop, and the proposed bit plane-synchronized closed loop.

A. Open Loop Prediction

As shown in Figure 4, in the *open loop* prediction, both the receiver and the transmitter use the original band for prediction. In the transmitter, the currently coded band B_i is predicted from band B_j using the prediction coefficients a_{ij} and b_{ij}. The predicted version of B_i, called P_i is subtracted from B_i to form the difference band D_i. The difference band D_i is then wavelet transformed into W_i and bit plane encoded to a bit rate required to achieve the target MSE. The receiver decompresses the truncated bit stream to $\hat{W}_i$ and then performs the inverse wavelet transform to compute the decompressed difference band $\hat{D}_i$. This difference is summed with P_i, the predicted version of B_i, to compute $\hat{B}_i$. Note that P_i is predicted from the original band B_j. Because in lossy compression, the receiver does not have access to the original band, this system cannot be implemented. Therefore, in our research, we use the open loop only as a reference system to compare with the results of other methods.

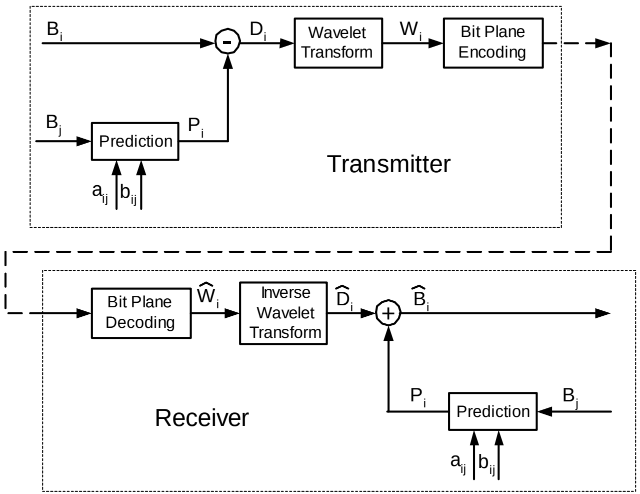


Figure 4. Open loop prediction.

B. Half-open Loop Prediction

Half-open loop prediction is a practical alternative to open loop prediction. In such a system, the transmitter uses the original previous band, while the receiver uses the previous decompressed band for prediction (see Figure 5). The transmitter is the same as in the open loop method. Because the receiver cannot use the original band B_j to predict band B_i, it uses the decompressed version of B_j, that is $\hat{B}_j$. The predicted version of B_i, $\hat{P}_i$, is summed with the decompressed difference band $\hat{D}_i$ to form $\hat{B}_i$. However, because the receiver and the transmitter use different bands for prediction, this method leads to a lack of synchronization between the transmitter and the receiver and thus large errors.

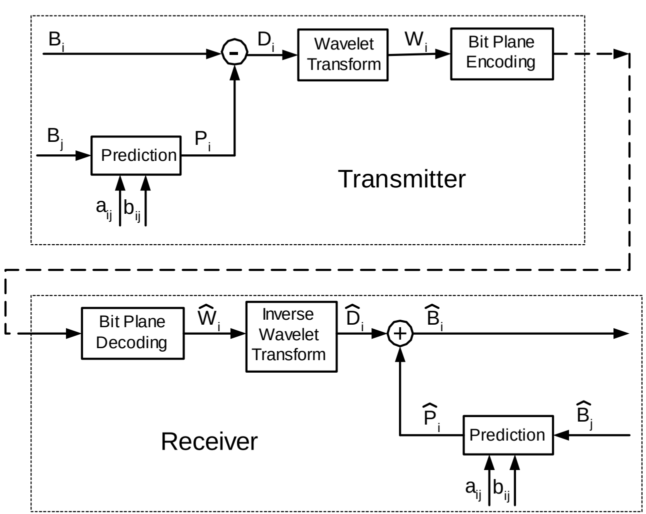


Figure 5. Half-open loop prediction.

Figure 6 shows the bit rate required to encode each band to the MSE of 100 in two cases: open and half-open loop. The average bit rate for the half-open case is 96502 bpp, while that for the open loop is 0.42 bpp.

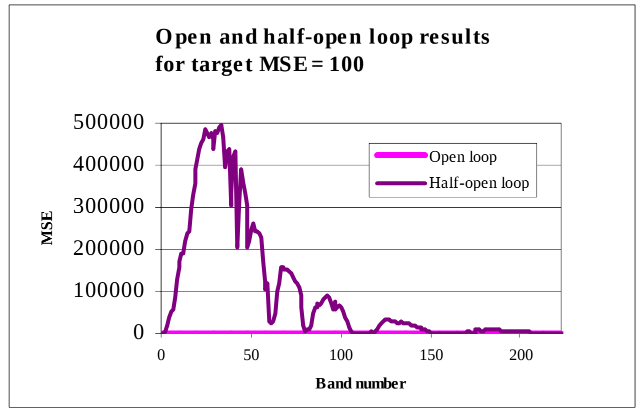


Figure 6. Results comparison for the open and half-open loops.

C. Closed Loop Prediction

In closed loop prediction, shown in Figure 7, both the transmitter and receiver use the decompressed band for prediction. It is the most accurate method, however it is also more complicated because it requires the transmitter to implement the decoder, which is computationally complex.

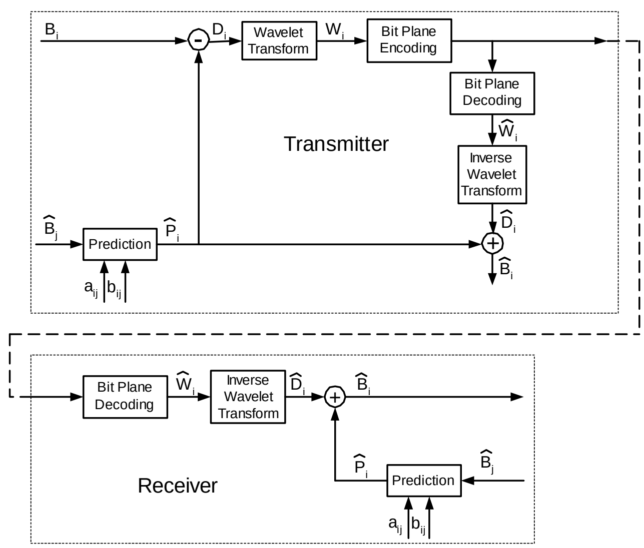
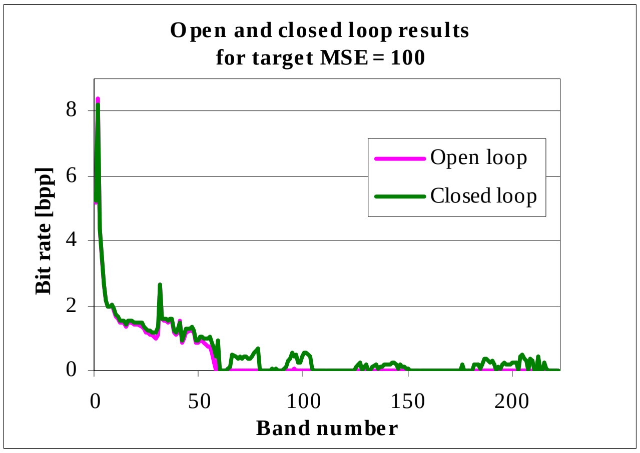


Figure 7. Closed loop prediction.

The transmitter uses the decompressed band $\hat{B}_j$ to predict $\hat{B}_i$. The predicted version of B_i, $\hat{P}_i$, is subtracted from the original band B_i to obtain the difference D_i, which is then wavelet transformed and encoded to a bit rate required for the target MSE. Then the difference is decompressed again to form $\hat{D}_i$, which is summed with $\hat{P}_i$ to form $\hat{B}_i$. The decompressed band $\hat{B}_i$ is stored in the transmitter so in the future it can be used to predict some other band B_k. The receiver is the same as in the half-open loop.

In Figure 8, we compare the results of the closed and open loops. The average bit rate to code all bands to the target MSE of 100 is 0.42 bpp for the open loop and 0.55 bpp for the closed loop. As can be seen from Figure 8b, the MSE is always below or close to the target MSE.



a)

b)

Figure 8. Comparison of open and closed loop prediction results. a) Bit rate. b) MSE.

D. *Bit Plane-Synchronized Closed Loop Prediction*

As a solution that is easier to implement on-board the satellite, we propose the *bit plane-synchronized prediction* shown in Figure 9. Both the transmitter and receiver use the same number of bit planes of the wavelet coded difference image of the previous band for prediction. We take advantage of the fact that the SPIHT algorithm can be split into two steps: wavelet transform and bit plane coding. The transmitter performs the wavelet transform on the difference band to get W_i and encodes it to the bit rate required to code the band to the target MSE. Once the target bit rate is known, the transmitter truncates W_i to the highest number of full wavelet bit planes such that the bit rate is still less than the target rate. We designate the truncated version of W_i by $\hat{\hat{W}}_i$. The inverse wavelet transform is then performed to obtain $\hat{\hat{D}}_i$ which is summed with the predicted version of B_i, that is $\hat{\hat{P}}_i$, to obtain $\hat{\hat{B}}_i$. This is the truncated and decompressed version of B_i that may be used later to predict some other band B_k.

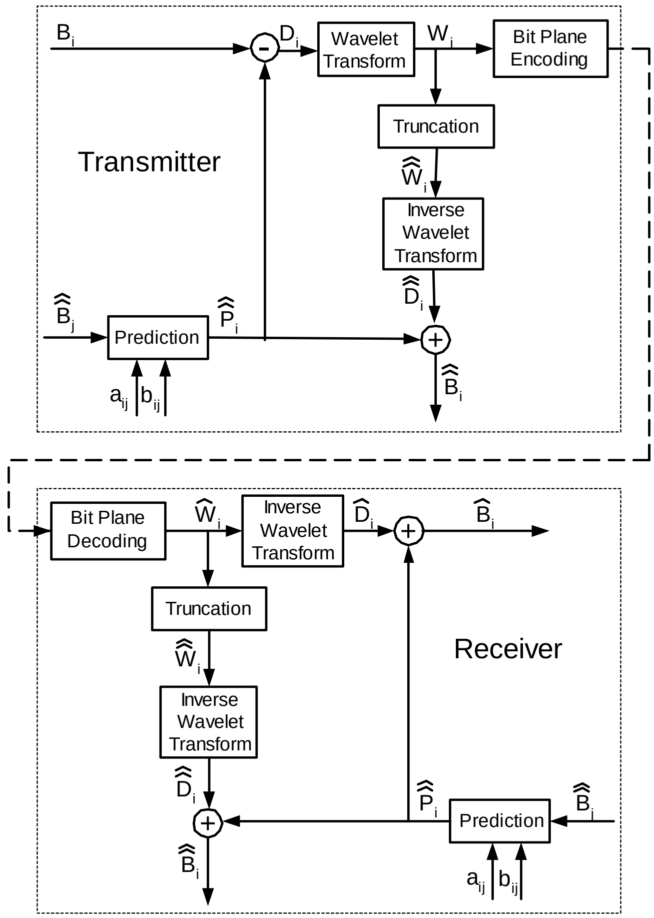
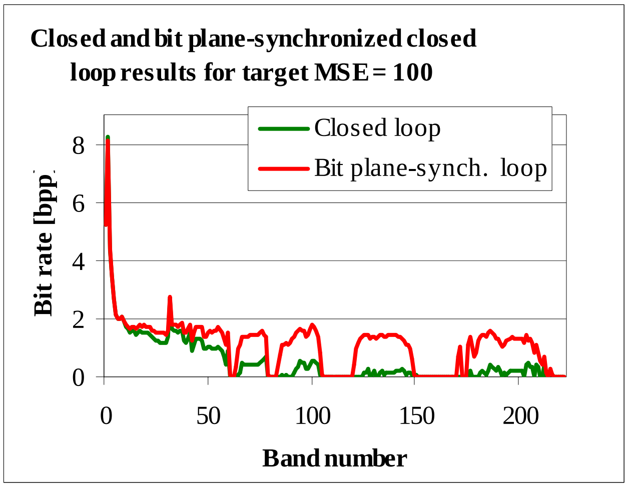


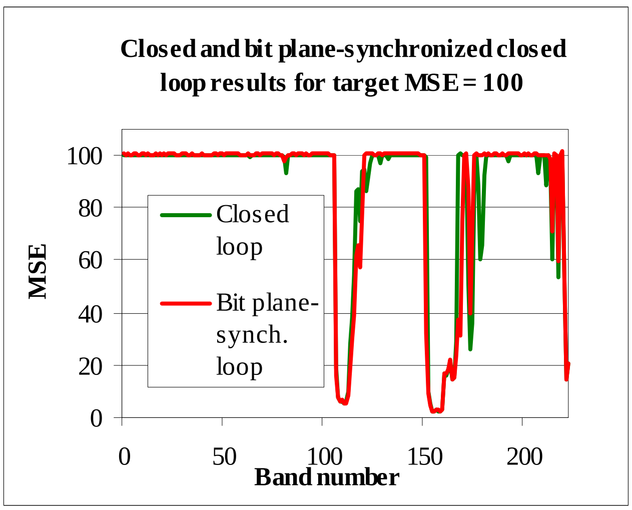
Figure 9. Bit plane-synchronized closed loop prediction.

The receiver in the bit plane-synchronized loop prediction uses $\hat{W}_i$ to compute the decompressed band $\hat{B}_i$ and $\hat{\hat{W}}_i$ to compute the decompressed truncated band $\hat{\hat{B}}_i$. The transmitter and receiver are always synchronized because they use the same data for prediction. This synchronization is achieved with a simpler on-board transmitter: it has to perform an inverse wavelet transform, but not a full decompression as part of the prediction process.

In Figure 10, we compare the closed and bit plane-synchronized loops. The average bit rate that is required to code each band to the target MSE of 100 is 1.12 bpp for bit plane-synchronized loop and 0.55 bpp for closed loop. The average MSE is similar in the two cases and equals 87.



a)



b)

Figure 10. Results for the bit plane-synchronized closed loop prediction. a) Bit rate. b) MSE.

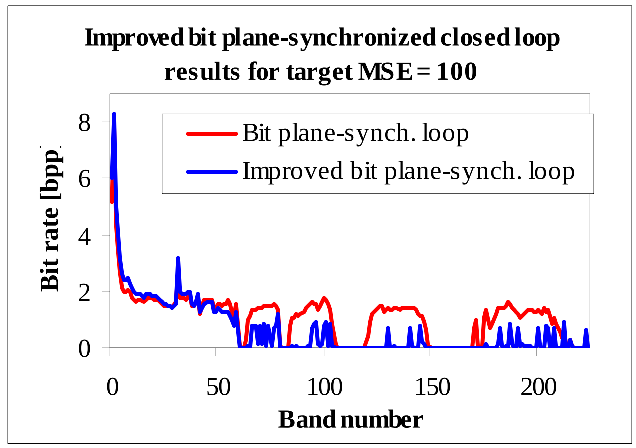
E. Improved Bit Plane-Synchronized Closed Loop Prediction

To improve the bit plane synchronized loop, we investigated computing new prediction coefficients and implementing rate control. Instead of simply truncating the wavelet transformed difference band, we can round up to the next number of bit planes. Our decision is presented in Equation (2),

$$|R(W_i) - R(\hat{\hat{W}}_i^{k})| < T|R(W_i) - R(\hat{\hat{W}}_i^{k+1})| \qquad (2)$$

where $R(W_i)$ is the rate required to code wavelet transformed difference W_i to the target MSE, and $R(W_i^k)$ and $R(W_i^{k+1})$ are rates required to code k and k+1 bit planes, respectively. If the statement in Equation (2) is true, k bit planes are selected for prediction. If it is false, k+1 bit planes are selected for prediction. Note that when k+1 bit planes are selected for prediction, the target rate has to be increased to that of the full k+1 wavelet bit planes. T is a threshold with typical values on the order of 0.1-1.0.

The results for the original and the improved bit plane-synchronized loops are shown in Figure 11. The average bit rate for the improved method is 0.65 bpp which is just slightly over the bit rate required in the closed loop prediction. In addition, the average MSE in the improved method is only 66, while the MSE of the original loop is 87. This result shows that the improved bit plane-synchronized loop is a very promising method to code hyperspectral data. It achieves a very good compression ratio with a low MSE and has a lower computational complexity compared to the original closed loop prediction.



a)

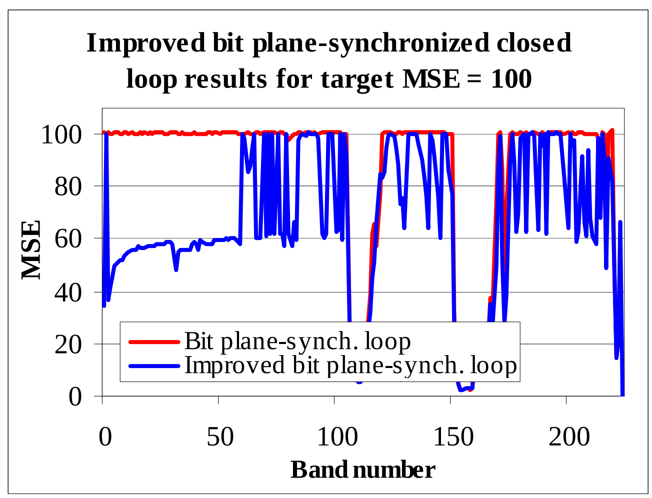


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Figure 11. Results for the improved bit plane-synchronized closed loop prediction. a) Bit rate. b) MSE.

V. Conclusion

In this research, we have investigated different methods of using prediction to code hyperspectral data. As expected, we saw that combining prediction with a state-of-the-art image compression algorithm significantly improves the compression ratio. We have also compared different methods of prediction (open, closed, and half-open loops) and proposed a new method, the bit plane-synchronized loop. We showed that under the constraints of a simple implementation on-board the satellite, bit-plane synchronized loop prediction offers excellent performance.

References

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